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Aeroservoelastic Characteristics of the B-2 Bomber and Implications for Future Large Aircraft

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Abstract. Design and development of the B-2 Bomber presented many challenges in flexible vehicle control, many related to the unique configuration and design requirements. The technical challenges posed by the aeroelastic characteristics of the all-wing aircraft were recognized at the outset of the development program and included the configuration's near-neutral pitch stability and light wing loading which made the aircraft highly responsive to atmospheric turbulence. This dictated the requirement for an active digital flight control system to provide both stability augmentation and gust load alleviation. The gust load alleviation flight control system was designed by a multidisciplinary team using a combination of optimal and classical control design techniques and a common analysis model database. Accurate representation of the vehicle aerodynamics characteristics, actuators, and sensors were key to successfully developing and testing the flight control system and verifying performance requirements. Flight test data analysis included the extraction of the vehicle open loop response which were utilized to adjust the analytical models and make final revisions to control law gains. The multidisciplinary design approach resulted in the successful development of a control augmentation system that provides the B-2 with superb handling characteristics, acceptable low altitude ride quality, and substantial alleviation of gust loads on the airframe. With this back drop, a technology assessment is performed which discusses potential technology improvements for application to future bomber and large transport aircraft.

Key words: Aeroservoelasticity, Gust Load Alleviation, Flight Test, Ride Quality, Structural Mode Control

1. Introduction

Design goals for the B-2 flight control system included aggressive gust load alleviation, good ride quality, and a stable platform for weapons deployment. The design effort required a multidisciplinary team approach involving structural dynamics, aeroelasticity, and flight control specialists. Design activities included refinement of the planform configuration, design and placement of control surfaces with the required control authority to meet flying qualities and gust load alleviation objectives, selection and placement of appropriate sensors, definition of actuator force, rate and bandwidth requirements, and synthesis of the control laws.

A common analysis database was utilized by all disciplines to ensure consistent, adequate performance with the final design. This database evolved from analytical models which were then revised as results of laboratory and flight test data became available. The flight test program showed the vehicle to possess more pitch stability than predicted by wind tunnel tests. This required adjustments to the analysis models and revision to flight control feedback gains. The flutter clearance wind tunnel test program was not designed to assess rigid body pitch/flex mode coupling at transonic speeds, and unpredicted response characteristics were later discovered during the flight test program.

This paper discusses elements of model development, methodologies used to design the gust load alleviation (GLA) control system, analyses to define gust design load requirements and verify aeroservoelastic stability, and the flight test program used for system verification. Recommendations will be discussed as appropriate, as well as a discussion of new innovative approaches to flexible vehicle control and analysis.

2. B-2 Configuration Overview

The B-2 is an all wing, high subsonic aircraft which utilizes three sets of elevons for combined pitch and roll control, a centerline gust load alleviation surface (GLAS) for pitch control, and upper and lower split drag rudders for yaw control. The planform and airfoil design are dictated from a combination of aerodynamic performance, control authority, and low observables requirements. At maximum fuel loading conditions the 1st flexible symmetric wing bending mode is less than 2 hz while for low altitude high speed conditions the short period mode can approach 1.5 hz.

The aircraft employs a full time active flight control stability augmentation system. Figure 1 shows a schematic of the quad redundant flight control architecture and major components. The feedback sensors used for active stability augmentation include the Air Data System (ADS) to measure the flight condition, aerodynamic angle of attack and angle of sideslip, and the Attitude Motion Sensor Set (AMSS) to provide inertial response data.

The Flight Control Computers (FCC's) functions include computing surface position commands in response to the feedback sensor inputs, pilot inputs, and guidance commands as well as redundancy management. The FCC's also interface with other elements of the avionics system.

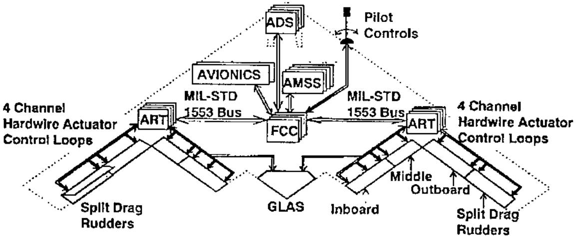

Figure 1 Flight Control Architecture

Paper presented at the RTO AVT Specialists' Meeting on "Structural Aspects of Flexible Aircraft Control", held in Ottawa, Canada, 18-20 October 1999, and published in RTO MP-36.

3. Analytical Models

Figure 2 shows the basic flow of modeling activities which supported the various analysis requirements. All models evolved from the appropriate databases. To support the many parametric analyses required to understand the vehicle response characteristics and to rapidly design effective realizable control laws, a low order structural model was desired. The aerodynamic formulation needed to reflect available wind tunnel test data, especially with respect to pitch stability, since a flying wing design is inherently marginally stable or unstable in pitch. The models also needed to be capable of including a representative model of the actuation system and sensors. MSC/NASTRAN was the primary tool for conducting the modeling activities and for performing the analyses for determining flutter speeds and gust loads. Elements of the NASTRAN solution were also used as input to a state space model formulation used for control law synthesis and analysis. Note that the flow of information through the system was driven by many different separate programs and analysis steps and was by no means automated.

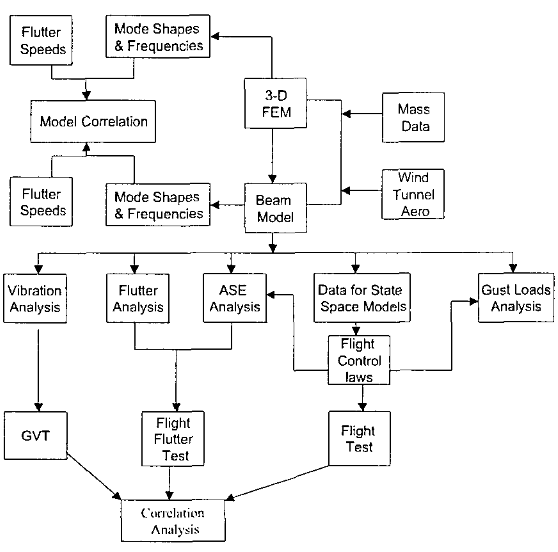

Figure 2 Model Synthesis

Structural Modeling

Basic structural and aerodynamic modeling was carried out in the MSC/NASTRAN[2] finite element modeling system. The majority of dynamic analyses utilized half-span models. Separate symmetric and antisymmetric response analyses being accomplished by inserting the appropriate centerline boundary conditions. A high order stress model was reduced for dynamic analyses and included over 10,000 elements, 3800 grid points and a reduced analysis set (A-set) of 631 degrees of freedom (Figure 3). A simpler 'beam' FEM was constructed for use in the many parametric analyses. The models were reviewed and modified as appropriate subsequent to the full scale vehicle ground vibration test.

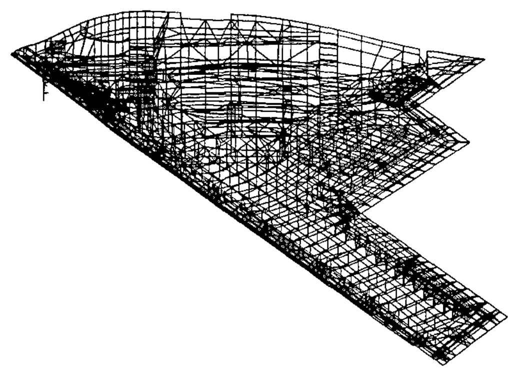

Figure 3 Half-Span Finite Element Model

Aerodynamic Modeling

The subsonic aerodynamic forces for both motion and gust induced angle of attack were generated from a half-span 384 box model (Figure 4) developed to satisfy reduced frequency requirements for both flutter and dynamic gust response analyses. The two dimensional Doublet Lattice Method (DLM) was selected to develop the unsteady forces.

Steady wind tunnel test data was available from testing performed on two models. The first model was 0.032 scale and the objective was obtaining an airloads database including the effects of controls and inlet mass flow. This model was tested in the Arvin-Calspan 8 ft by 8 ft transonic tunnel. A second model of the 0.06 scale was tested in the PWT 16 foot tunnel. Test objectives included obtaining data for basic stability, control effectiveness, Reynolds No., and airloads verification.

Comparisons were made between the low frequency prediction of the Doublet lattice model and certain parameters derived from measured data. Coefficients of particular concern were the spanwise distributions of lift curve slopes and aerodynamic centers, and the total pitching moments due to control surface deflection. These were developed from pressure distributions at angles of attack representative of trim. These are important parameters relative to the assessment of basic vehicle pitch stability and for developing active control schemes for ride quality and gust load alleviation. A correction factor program (reference 3) was utilized to develop weighting factors which when applied to the DLM aerodynamics insured that the spanwise distribution of lift curve slopes and aerodynamics centers matched wind tunnel test data. The weighting factors are applied directly to the box forces in NASTRAN (via DMAP Alter) and, therefore, apply to all modes. The correction factor methodology was unable to generate factors which would also satisfy the pitching moment due to control surface deflection constraint and therefore they were handled as part of the gain scheduling in the active system implementation. Figure 5 shows the aerodynamic model box layout with the values of the factors shown on the figure.

Since the correction factors were generated for steady flow conditions the application of them to all reduced frequencies was reviewed. Early flutter analysis comparisons with both low and high speed flutter model test results demonstrated

that the flutter phenomena could be successfully predicted without the aid of correction factors, and therefore it was decided to schedule these factors as a function of reduced frequency. A reduced frequency of 0.4 was chosen as the point at which all the correction factors would become unity. This value was recommended in reference 21. Therefore, the factors generated for each box force coefficient were linearly interpolated with reduced frequency so as to become unity at a reduced frequency of 0.4.

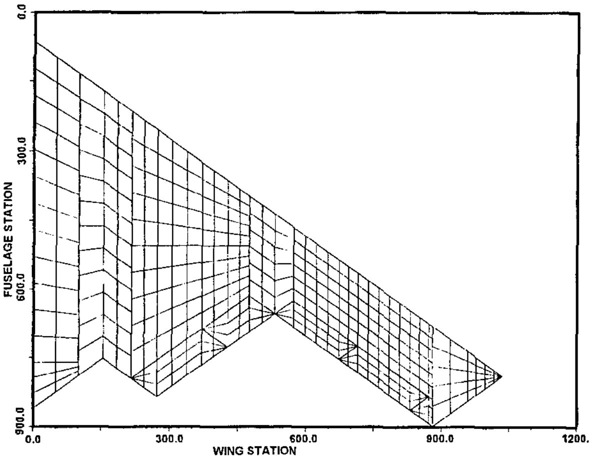

Figure 4 Doublet Lattice Model

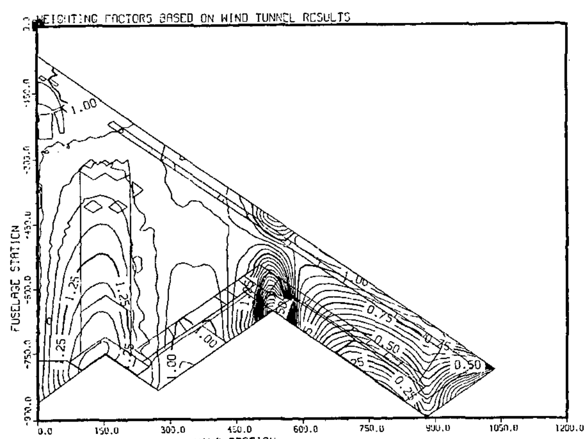

Figure 5 Weighting Factor Distribution

Frequency Domain - State Space Conversion

MSC/NASTRAN was utilized to generate the basic data necessary to transform the 2nd order frequency domain equations of motion into a state space formulation required for flight controls design tasks. Generalized mass, stiffness and aerodynamic matrices (both motion dependent and gust disturbance) were the starting point for this model. A subset of the physical degrees of freedom in the mode shapes were provided at locations of interest so that physical motions could be recovered to define sensor feedback outputs and forces developed by the actuation system. Bending moment modal coefficient data were also provided.

Conversion into a state space formulation[4,16] requires a frequency domain approximation of the doublet lattice aerodynamics. The method of reference 17 was used for this purpose. The resulting analog state space models retain 2 rigid body (pitch and plunge) modes, 16 flexible modes, four control surface inputs, and a gust disturbance input. The analog state space models generally have about 100 states. The large number of states utilized by the method of reference 17 limited the number of structural modes that could be retained. The use of alternate aerodynamic approximations, which feature a smaller number of states, has not been explored on the B-2 but would be recommended for future development work.

Excellent agreement between the NASTRAN frequency domain solution and the state space model was achieved as seen from the comparison of Figures 6. Close agreement is absolutely mandatory if control law performance is going to be consistent between the two models.

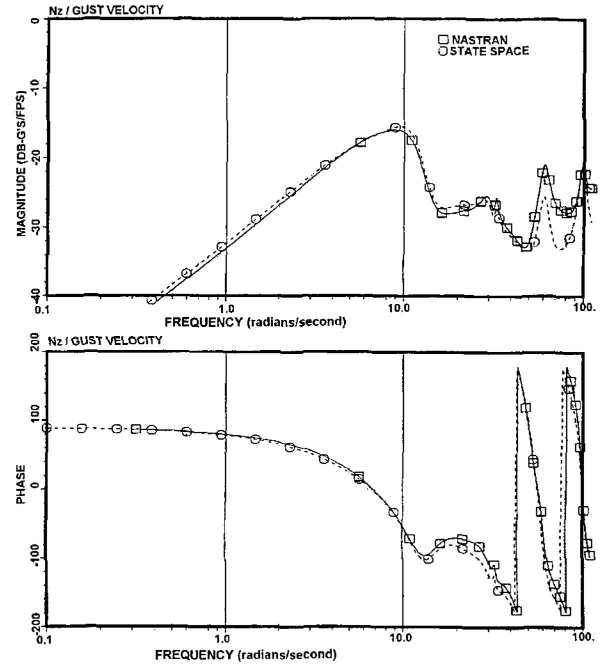

Figure 6 Response due to Gust

Actuator Modeling

A model of the actuation system was required in both the NASTRAN formulation and the state space model. The actuator was modeled as a force-producing element between the control surface and back-up structure rather than as an enforced deflection. This allows the dynamics of the combined actuator and control surface to be reflected in the analysis. In NASTRAN the multi-point constraint (MPC) feature is used to define relative motion using *scalar point* degrees of freedom. The block diagram in Figure 7 shows the general form of the model[1]. The actuator includes an outer position control loop and dynamic pressure feedback control loop to dampen the control surface resonance modes at low dynamic pressure (or low aerodynamic damping). *Extra point* degrees of freedoms are used to define other block diagram variables. The transfer function (TF) option is used to define the actuator model in NASTRAN. Figure 8 shows the actuator and surface response to command, illustrating the surface dynamics included in the model.

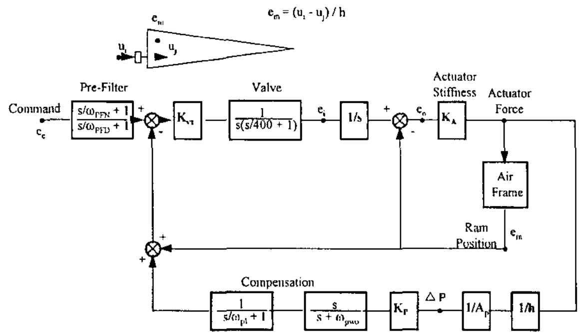

Figure 7 Actuator model

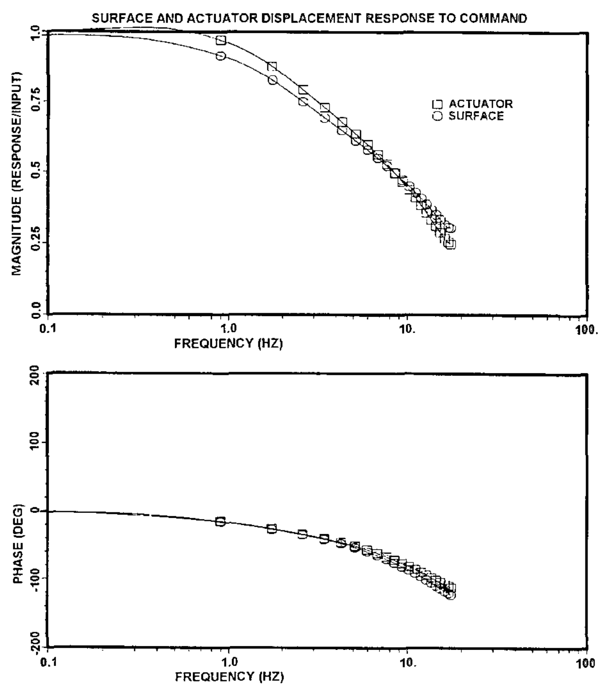

Figure 8 Surface Response to Command

Actuator dynamic stiffness and hinge line back-up stiffness can be included in the basic structural model which produces the vehicle modes. An alternative approach is to omit these springs in the modal analysis and add them back in at the modal level when the actuator equations are added to the equations of motion. The latter approach, using a truncated set of structural modes, leads to greater accuracy than the former. The actuator model shown in the block diagram of Figure 7 is for the zero frequency control surface mode formulation.

This model of the actuator allows the calculation of actuator rates which can then be used to determine practical gain scheduling based on realizable surface rates. The model is extendible to use in non-linear simulations where the effects of actuator rate and deflection limits, hinge moment limiting, and actuator hydraulic pressure limits could be assessed.

Digital Effects

Early flight control analysis showed the high bandwidth required for effective GLA performance was sensitive to the phase degradation of feedback signal data latency and digital implementation. To minimize these effects, a "bottom up" approach was taken to define performance and throughput requirements for the sensors, MIL-STD-1553 multiplex bus traffic and timing, FCC timing and throughput calculations, actuator bandwidths, and surface rates.

Feedback signal data latency was defined and included into the digitized models as partial and full frame delays. Feedback data latency is the finite time delay measured from the analog air vehicle motion or state feedback, through the Flight Control Computer (FCC) surface command calculations to the actuator command at the Actuator Remote Terminals ARTs. The digital response in Figure 9 shows the phase lag due to throughput and digitization effects compared to the analog response.

Analog filters were developed to approximate the ratio of the open loop digital and analog model frequency responses. These filters were then applied to the NASTRAN analog model to approximate the GLA performance with the digital and throughput delay effects. Figure 9 shows how these analog filters adequately approximate the digital model response up to 70 radians/second, which is well beyond the GLA controller frequency range of interest. Flutter analyses included additional filters to assess the impact of phase shifts beyond this frequency.

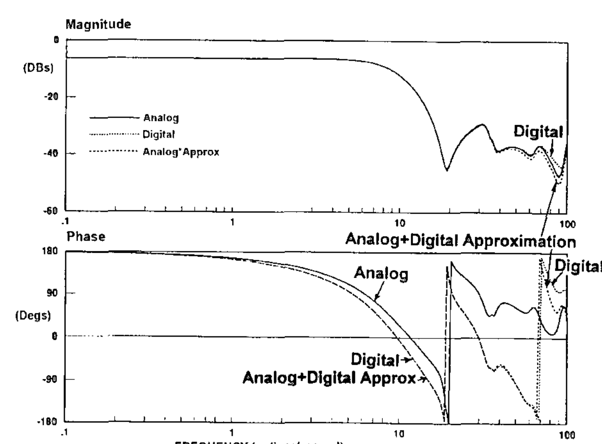

Figure 9 Open Loop Pitch Rate to Inboard Elevon

4. Gust Load Alleviation(GLA) Summary

Gust load alleviation control of the B-2 involves quickly pitching the aircraft into the gust to control the build up of gust angle of attack and thereby minimize normal acceleration and structural loads. Effective gust load alleviation performance requires a high bandwidth pitch control augmentation system with high control surface rates. Lateral gust load alleviation was not required due to the low projected side area.

Figure 10 shows an example of the centerline bending moment gust load alleviation performance achieved on the B-2. Generally, the GLA controller performance reduces incremental gust loads by up to 50% when compared to an

open loop (unaugmented) model, or a closed loop handling qualities controller design. Similar ride quality improvements are also attained.

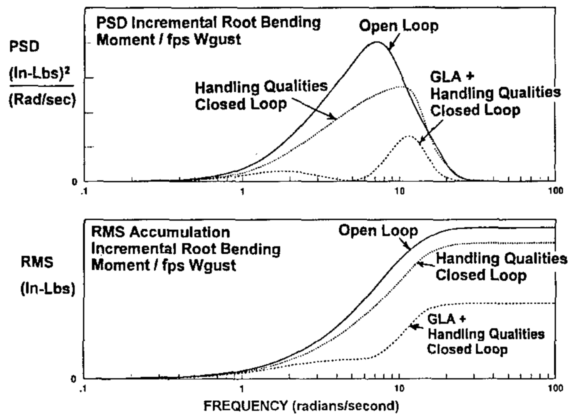

Figure 10 GLA Performance

Gust design load requirements were derived from continuous turbulence analysis criteria[8] and are greater than maneuver requirements over a significant portion of the inboard wing. Considerations related to development of phased load design conditions for structural analysis followed approaches similar to those in reference 9. Effects of control system nonlinearities at peak gust conditions were included, also in a manner similar to those in reference 9. Non-uniform spanwise gust effects have also been examined for the B-2[10].

Gust Load Alleviation Controller Development

The Pitch Control Augmentation System (PCAS) GLA synthesis utilized classical and modern control theory methods. Piloted simulation was used to verify and adjust, as required, the predicted handling qualities.

Optimal controller results were used to bound the achievable GLA performance and focus development of a classical multiple input multiple output (MIMO) design. Each feedback loop was confirmed by classical analyses and a solid physical understanding before implementation. This quickly eliminated many ineffective "optimal" gains, and retained the available elevon surface rates for the best control loop GLA performers.

The B-2 PCAS achieves consistent Level 1 handling qualities throughout the flight envelope using a load factor and pitch rate proportional plus integral (NZQPPI) design. GLA performance is achieved with a combination of NZQPPI low frequency control and a *gust sniffer* loop for mid and high frequency control. The *gust sniffer* loop senses the aerodynamic gust angle (Figure 11) of attack by subtracting the inertial angle of attack from the total (inertial + gust) aerodynamic angle of attack at the nose. Feedback gains, loop shaping compensation, and surface utilization mixing are scheduled with flight condition.

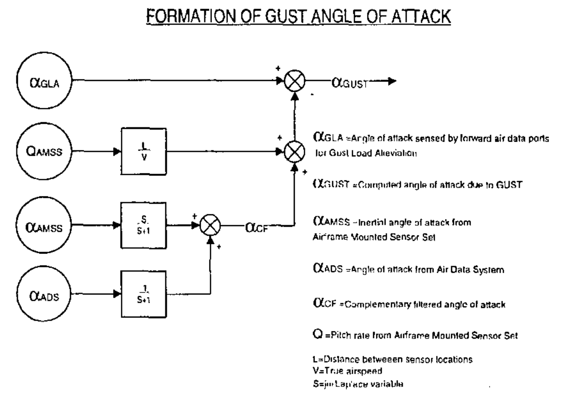

Figure 11 Gust Angle of Attack

Pitch Control Surface Utilization

Innovative pitch control surface mixing is used to provide active flexible mode damping at low and high altitudes. Figure 12 shows the node line of the first flexible symmetric mode. Aggressively pitching the B-2 into vertical gusts at low altitude using the GLAS and Inboard Elevons significantly reduces the low frequency rigid body gust response, but tends to excite the first flexible mode. Since the Outboard Elevon is outboard of the node line, commanding it out of phase with respect to the Inboard Elevon dampens the first flexible mode response. The Outboard Elevon also provides local high frequency direct lift control by decambering the local wing chord.

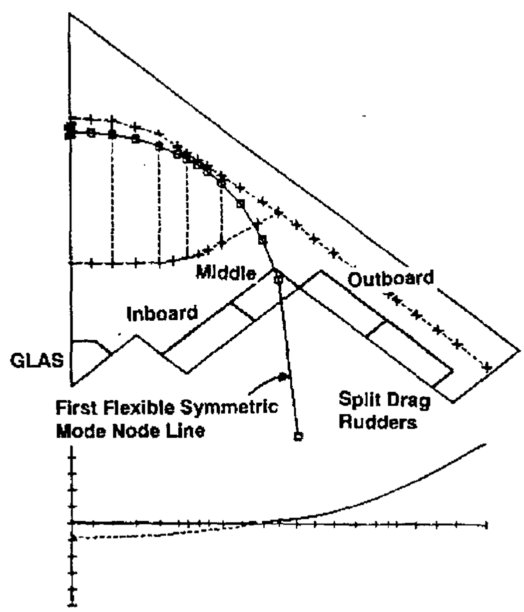

Figure 12 1st Flexible Symmetric mode

Figure 13 shows the effectiveness of utilizing the outboard elevon out of phase in reducing the center line bending moment.

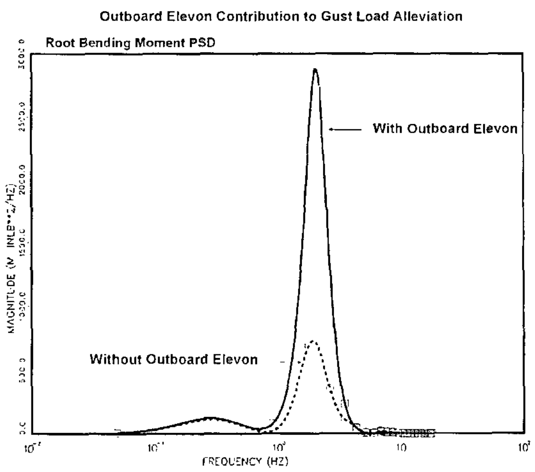

Figure 13 Effectiveness of Outboard Elevon

Reduced aerodynamic damping at high altitude produced a significant flexible mode contribution to the total pitch control loop for heavy outboard fuel conditions. An innovative control surface mixing concept, referred to as the *Inertial Damper*(reference 18*)*, was developed to minimize the excitation of and dampen the 1st flexible mode while still maintaining the required control loop bandwidth. Flight test data in Figure 14 shows how the *Inertial Damper* surface mixing achieves the desired flexible mode gain attenuation without incurring the additional phase lag from a classical notch filter implementation.

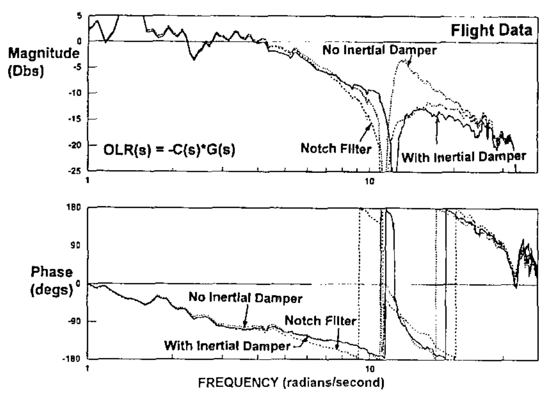

Figure 14 High Altitude Inertial Damper

5. Flutter Analysis

Matched point flutter analyses were performed using the PK solution in NASTRAN. Both symmetric and antisymmetric analyses were conducted. Matched point flutter analyses including the active flight control system were also performed. The spanwise stiffness distribution of the graphite composite wing box of the B-2 was tailored to achieve a wide separation between the fundamental bending and torsion frequencies. As a consequence the basic flutter speeds were predicted to be well outside of the required flutter boundary. The minimum flutter speed condition involved coupling between antisymmetric 1st and 2nd bending and 1st torsion modes. The flutter frequency was approximately 9 hz and the flutter speed was well outside the required envelope.

A series of wind tunnel tests, both high and low speed were performed during the development program. One low speed test featured a model which was cable mounted and included an active system for dynamic pitch control. Correlation of this test with analysis was excellent and provided confidence in the modeling analysis procedures.

There were a series of three transonic flutter model entries. Two entries were wall mounted semispan models of 3.5% scale. The third entry was of a full span model on a sting of 1.75% scale. A set of flutter speed correction factors was developed from the semispan models by comparing test results with corresponding analysis of the flutter model. The full span model was used primarily to verify that the antisymmetric flutter mechanism produced the lowest flutter speed. None of these tests were able to evaluate the interaction between the pitch mode and the flexible modes of the vehicle.

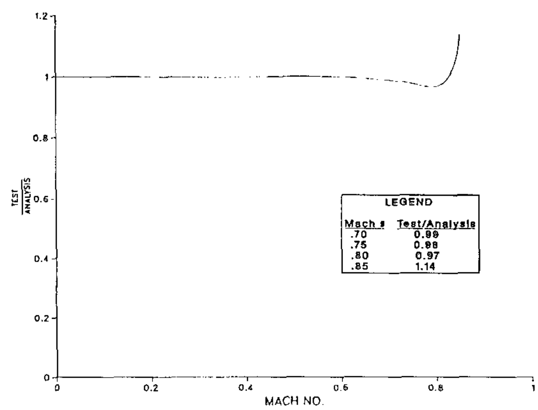

Figure 15 Transonic Flutter Speed Correction

6. Flight Testing

Flight testing (reference 12 and 18) was conducted to verify that flutter, flying qualities, and other dynamic response characteristics were satisfactory. Because of the highly augmented flight control design, integrated flight control and flutter flight tests were required during envelope expansion.

The vehicle was dynamically excited by oscillating the control surfaces. This was accomplished with pilot pitch and roll stick inputs or by special test hardware (Flight Control Test Panel (FCTP)), mounted in the cockpit. The bandwidth of the actuation system, together with the size of the B-2 control surfaces, was sufficient to provide effective excitation of the air vehicle. Frequency and damping could be readily determined from the recorded data.

The final test matrix for flutter clearance did not include the assessment of payload effects. Test schedule and asset availability required a continual review of test requirements. Low speed wind tunnel flutter model testing and extensive parametric analysis did not indicate flutter sensitivity to payload so these points were not flight tested.

Subsequent flight controls clearance testing with payload showed an apparent coupling between the rigid body pitch

and first wing bending mode at a Mach number just beyond the operational limit. This has been reported in references 19 and 20 and referred to as Residual Pitch Oscillation or RPO.

7. Flight Test Matching/Model Update

Full time active flight control augmentation requirements prohibited testing with the augmentation disengaged. Control surface effectiveness, surface mixing, and short period/flexible mode interaction are important to both the B-2's high altitude *Inertial Damper* and low altitude high speed GLA performance. Verification of the accuracy of the open loop aeroservoelastic model, therefore, was necessary.

B-2 flight test data parameter identification and model matching attempts using NASA's MMLE3 (Modified Maximum Likelihood Estimator[14]) program gave inconsistent results, with wide variations in model estimates between very close flight conditions, for all except the basic dominant derivatives. Parameter identification was further complicated by the sensitivity of closely coupled flying wing aircraft to differential motions between the structural(sensor) and mean inertial axes[15]. While early flight test results verified the basic aeroelastic stability and flying quality performance, detailed correlation with the analytical models indicated that some aerodynamic terms required adjustments.

The flight data verification bypassed the difficulties and limitations experienced in the past by directly developing open loop frequency domain "Flight Data Models", G(s), from the closed loop responses. The open loop "Flight Data Models" (FDMs) permitted direct frequency domain comparisons with the aeroservoelastic models, closed loop design performance verification, and flight test based analysis confirming proposed design adjustments. Quasi-steady low frequency (wind up turn) flight test results compared reasonable well with predicted wind tunnel data. The FDMs successfully captured the effects of the unsteady aerodynamics and flexible vehicle interaction for the mid frequency range near and around the short period and first symmetric flexible mode. The high altitude *Inertial Damper* was efficiently tuned using the open loop FDMs.

Figure 16 shows the open and closed loop MIMO FDM frequency response matrix format. Closed loop time response flight test data to individual pitch control surface random excitations were collected using the Flight Control Test Panel. High coherency frequency responses of the closed loop outputs to the known random surface excitations were then constructed during post flight analysis, and included in the appropriate column of the closed loop frequency response matrix Gcl(s). C(s) is the "constant" MIMO Controller for the tested condition. By keeping the vehicle configuration and flight condition constant, the only unknown in the closed loop equation is the open loop frequency response G(s), shown in Figure 16.

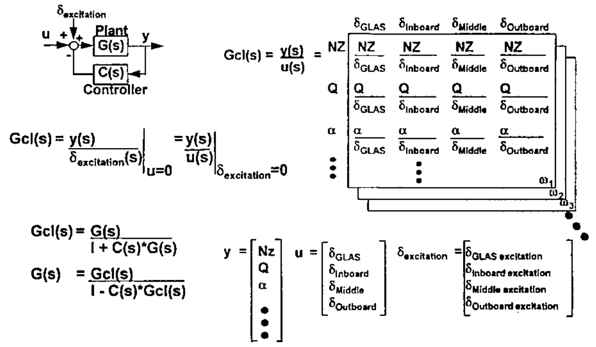

Figure 16 Open Loop Response Calculation

The vehicle configuration gross weight, center of gravity, and fuel distribution were kept approximately constant by collecting all the necessary individual surface excitations for a given flight condition in rapid succession. The flight condition was kept constant by using the autopilot to maintain pitch attitude and thereby trim altitude and angle of attack. The pilot's only task was to maintain the desired speed condition using slow smooth throttle movements. Keeping the pilot's hands off the stick eliminated any "disturbances" in the closed loop response due to unknown and adaptive human pilot control loop inputs.

The open loop MIMO FDM compared well with the open loop quasielastic (rigid + elastic corrections) and aeroservoelastic models. Increased pitch stability and variations in individual surface effectiveness were noted. Comparisons were also made of the total pitch control open loop return (OLR= -C(s) *G(s)) developed from a single pilot pitch frequency sweep and the open loop FDM. Figure 17 shows a good match between approximately 2 to 40 radians/second which was the frequency range of interest and where the individual surface excitation power was concentrated.

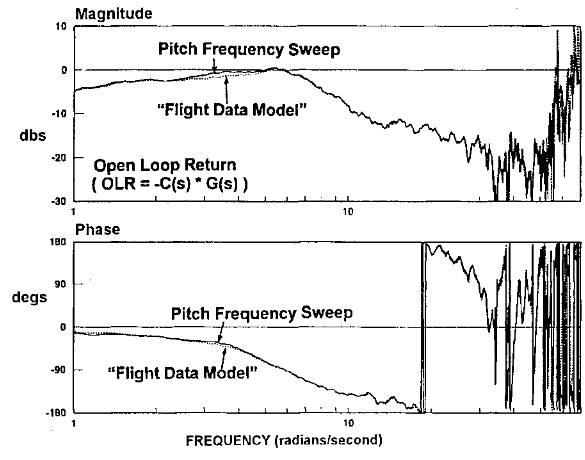

Figure 17 Flight Data Model

Post flight analysis compared the FDMs with the predictions of the NASTRAN model. Flight data analysis indicated that the vehicle had more static stability than predicted. A uniform adjustment (% MAC shift) in aerodynamic center was made across the span of the wing by modifying the aerodynamic weighting factors as shown in Figure 18. Figures 19 shows good agreement of the adjusted NASTRAN models and FDMs.

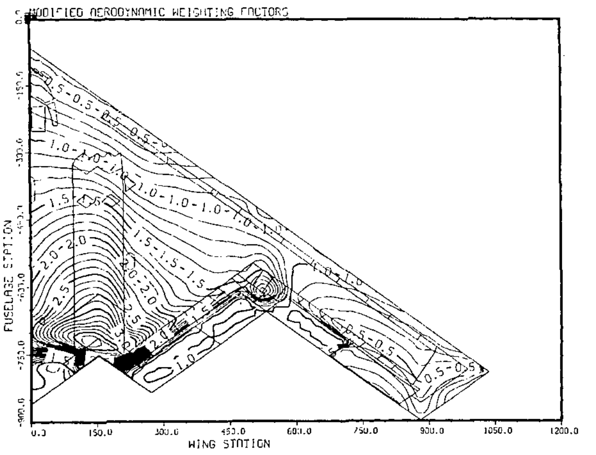

Figure 18 Flight Test Adjusted Weighting Factors

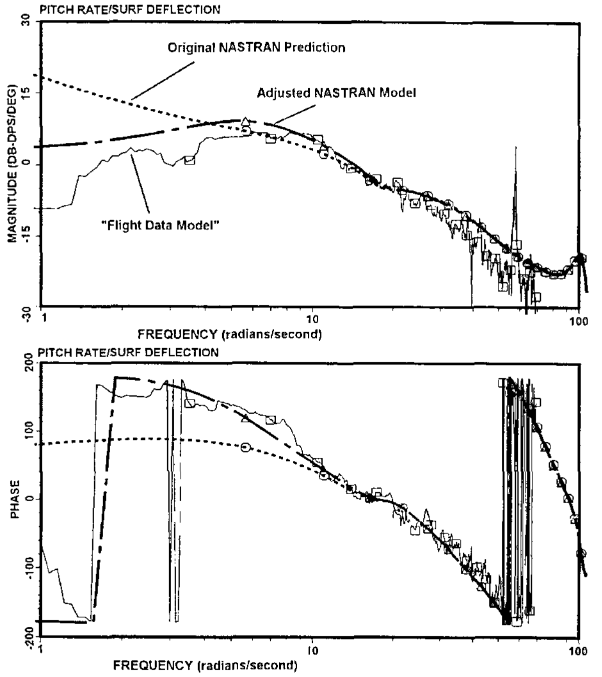

Figure 19 Open Loop Pitch Rate to Inboard Elevon

8. Residual Pitch Oscillation

The B-2 aircraft encountered a nonlinear aeroelastic Residual Pitch Oscillation (RPO) during low altitude high speed flight testing. The RPO response was observed after control surface pitch doublets were input at flight conditions outside the operational envelope. The initial air vehicle response decayed in amplitude but transitioned to a small, constant amplitude, residual pitch oscillation after several cycles (See Figure 20).

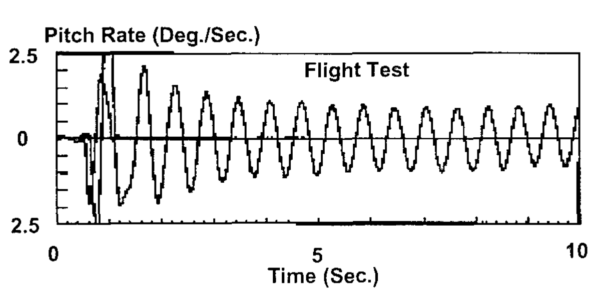

Figure 20 - Typical RPO Response To Pitch Doublet

The RPO phenomenon was not predicted by analytical methods to this point in the program, was not observed during low or high speed wind tunnel flutter testing, and was not observed during the previously completed flight flutter testing. Aeroelastic models using linear aerodynamic representations were incapable of capturing RPO. The low speed wind tunnel testing lacked the effects of transonic flow. When the high speed wind tunnel flutter model was designd it was decided to mount it rigid and avoid the complexity of making the model free flying since the flying wing was statically unstable for certain conditions. This prevented detection of RPO during the high speed wind tunnel programs. RPO was not observed during the flight flutter test program because the most RPO critical configuration of heavy payload and forward center of gravity condition had not been included in the final test matrix.

After the RPO was encountered, 11 dedicated flights were flown to collect data to better understand the phenomenon and to define the on-set boundaries. Figure 21 shows typical vertical load factor responses to pitch doublets as an RPO condition is approached by slowly increasing Mach number in level flight. The response transitions from being highly damped to being oscillatory with a relatively small increase in Mach number. During the flight program, conditions of zero damping were encountered on the critical heavy weight configuration.

Analysis of the RPO flight data did not show the characteristics normally expected of a classical flutter phenomenon. An oscillating shock was visible in the condensation cloud over the engine nacelles during some of the forced response tests. Flight test data indicated that the aircraft aerodynamic center moved aft by as much as 3 feet as the RPO Mach was approached.

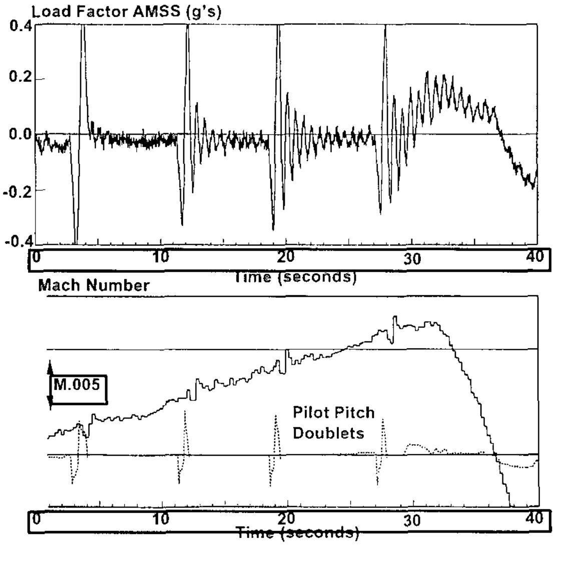

Figure 21 - Pitch Response Approaching RPO

Two analytical model development approaches were initiated to increase the understanding of the RPO phenomenon and investigate potential fixes. The first approach assumes that the unsteady air loads in the transonic regime can be represented as the superposition of linear theory and a supplemental linearized transonic shock force doublet. Model solutions are performed in the frequency domain with

conventional methods. The shock force doublet phase lag relative to angle of attack could be tuned to produce a zero damped condition. The second approach utilized the time marching computational aeroelastic method of NASA Langley's CAP-TSDv code. Good success was achieved with CAP-TSDv in simulation of RPO. Details from these studies have been reported in References 19 and 20.

These studies combined with the flight test results, provided insight into the RPO mechanism. As the vehicle airspeed is increased toward RPO, shock formation on both the upper and lower surfaces cause an aft shift in the aerodynamic center. This increases the static stability and increased the frequency of the rigid body short period motion. For low altitude high speed conditions, the increased short period frequency causes an interaction with the 1st symmetric wing bending mode (for certain configurations). As RPO oscillations ensue, the shock locations become oscillatory and participate in the aeroelastic phenomenon. The constant amplitude residual pitch oscillations (as shown in Figure 20) were determined to be caused by deadband in the control surface actuators and to occur at conditions where the critical mode damping was small.

A Mach number overspeed protection warning was developed to help the pilots avoid encountering an RPO outside the operational envelope. The primary concerns that required avoiding the RPO included undefined structural loads in an RPO with turbulence and reduced fatigue life considerations, flying qualities, and safety of flight considerations. This system includes an audio warning to the pilot which is a function of the configuration, current Mach number, and acceleration rate. Pilots are alerted to reduce thrust to slow the acceleration when approaching a potential RPO condition. Piloted simulator and flight test evaluations were performed to show that the Mach overspeed protection system provided good lead time indications so the pilots could avoid RPO.

10. Technology Assessment

This section of the paper, in light of the B-2 aeroelastic and aeroservoelastic design challenges presented, assesses technology needs for a future heavy bomber or transport of a similar configuration. Technologies assessed will include those to improve the design process, as well as consideration of emerging hardware concepts.

Design Methods

Areas of recent research activity relating to improved design tools for aeroelastic and aeroservoelastic design can be categorized into two areas, 1) High Fidelity Simulation and Test 2) Multidisicplinary Design Environment.

A recurring theme related to areas needing improvement is in the area of aerodynamic analysis and test, both steady and unsteady. For example, the RPO condition previously discussed was not predicted by either analysis or test, primarily due to the inability to capture transonic shock oscillations. The high speed flutter model used during B-2 design development was fixed on a sting, therefore the rigid body modes that are key ingredients of the phenomenon were not represented. A high speed flutter model to predict RPO would have required an unrestrained model with an active control system. This was not deemed practical, and it is unlikely that this is a viable avenue for future programs. Scaling issues in themselves are intractable, for example actuators do not scale down well and would likely impose mold line bumps which may significantly influence results.

A more affordable practice may be to perform unsteady (forced oscillation) wind tunnel tests where pressure data is captured, then imported into analytical models. It is possible that sufficient data would have been available to capture the B-2 phenomenon if such a test and analysis were performed, however boundary layer and shock scaling need to be considered carefully. Such tests with flexible models would be preferable, but not always necessary, and may not be practical with high Reynold's number loads.

The CAP-TSDv code was able to simulate the RPO condition *after the fact,* requiring a significant effort to extend the code's capability to include rigid body modes and an active control system. Even though chosen over other CFD based aeroelastic tools for computational efficiency , each time accurate RPO simulation takes approximately 8 hours of CPU on a high end multiprocessor workstation. Considering projected advances in computational performance it is still doubtful that the number of simulations required to capture like phenomenon could be accomplished in a manner consistent with vehicle program development schedules. Navier-Stokes based aeroelastic CFD approaches would take at least an order of magnitude more compute time than CAP-TSDv. For this reason research into Reduced Order Methods is of interest, such that results of high fidelity aerodynamics codes may be used in quick turnaround aeroservoelastic, flutter and static aeroelastic analysis. aeroelastic analysis. The duration of time required to assemble and execute a high fidelity analysis to simulate behavior such as the B-2 RPO
is of concern. The extensive, focused effort also resulted in a procedure with many elements specific to the B-2. Modifying the code for each new applications will require problem specific changes. The ability to quickly assemble and execute high fidelity aeroservoelastic systems is imperative to minimizing the likelihood of future problems such as RPO, as
well as addressing issues that do arise.

Regarding the multidisciplinary design environment, recent research emphasis has been on developing multidisciplinary frameworks for design and analysis. One representative system in development is the MultiDIsciplinary Computational Environment (MDICE)[22] activity funded by the Air Force Research laboratory (AFRL). The strategy of this design framework is that of the loosely coupled systems - a framework where user selected CAD and CAE tools may be 'mixed and matched' to perform model generation and multidisciplinary analysis. The MDICE software is a graphically driven, object oriented system providing dynamic data sharing, execution control and synchronization. A key element of the system are interdisciplinary interfaces - such as algorithms to connect fluid-structure boundaries. MDICE hosts a library of interface routines selectable by the user, as well as the ability for the user to attach routines of choice. Various aeroelastic applications have been demonstrated[23], with plans to extend demonstrations to aeroservoelasticity.

MDICE is just one of many frameworks being developed for engineering design environment automation. Maturation and implementation of systems to conveniently and robustly couple engineering design disciplines is imperative to cost effective future design and development programs. The ability to *selectively* incorporate high fidelity modules is a very attractive feature of loosely coupled systems.

Actuation and Sensor Technology

A problem area typically encountered to some levels in vehicle development is accurate determination of vehicle body axis rates. Flexible modes are typically filtered out by notch filters. Resulting phase lag reduces system stability margins, and sensor noise causes design and performance issues. To address this, under the AFRL AMICS[24] program, a Rigid Body Synthetic Sensor (RIBS) approach was designed and tested analytically. This approach proposed a distributed sensor network whose data was processed by neural network algorithms, providing spatial filtering. The test demonstrated the ability of the RIBS approach for control law state system feedbacks which could be used both in the design process, as well as real time on board sensing. Research and development is continuing in the microsensor area such that they could be affordably implemented into vehicle structure. Micro gyros are projected to have unit costs under $10. Figure 23 presents a high level schematic of the RIBS approach for lateral directional rate sensing.

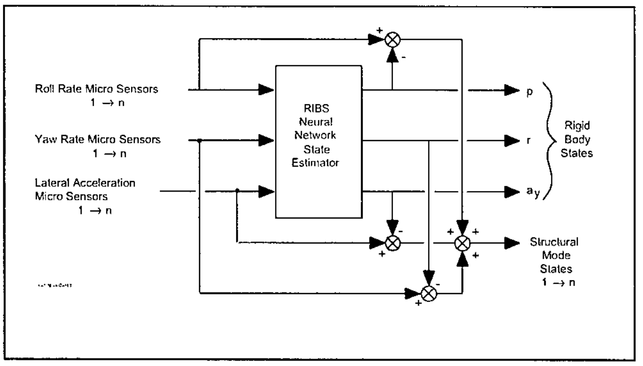

Figure 23 - RIBS Simplified Block Diagram for the Lateral-Directional Axis.

Much of the research in advanced actuation is in the area of electric actuators. The primary motivation is to reduce manufacturing costs and maintenance costs by replacing costly hydraulic systems with potentially lower cost electrical ones. Both electromechanical (EMA) and electrohydrostatic (EHA) actuators are being developed. The electrohydrostatic actuators are self contained units incorporating electrically driven 'local' hydraulic systems which power the individual actuator. The DARPA Fly-By-Light Advanced Systems Hardware (FLASH)[25] program is performing modeling, analysis, testing and system demonstration of EHAs.

The B-2 requires relatively high bandwidth control actuation due to the inherent instability of the system and the GLA system requirements. Slight lags are induced by the centralized hydraulic system, but somewhat larger lags are realized by the direct valving system. This valving system also resulted in some secondary ringing in conjunction with the RPO phenomenon, as reported in the previous section. In general the lags were manageable, the primarily impact being increased control system design costs to model and accommodate the lags to meet system requirements.

Electrohydrostatic actuation is a promising technology, however most of the gains are related to overall system level benefits (lower cost, improved reliability and maintainability) with goals to meet current conventional actuation performance. Lags due to valving may be addressed in a similar manner whether conventional or EHA, so this may not be a significant discriminator. Lags due to distance from the centralized unit of conventional systems are eliminated.

Electromechanical actuators also strive for similar system level benefits as the electrohydrostatic. A clear benefit would be the inherent near zero lag of electromechanical systems. However there is a tradeoff in bandwidth due to the large amount of gearing required. ElectroMagnetic Interference (EMI) of the actuator is an area that also needs to be addressed. In the cases of both the EHA and EMA, fiber optic control is proposed and has been demonstrated. Fiber optics provide data rates that easily meet specification, however both systems require power distribution by electrical cabling which is being evaluated for cost, reliability and maintainability vs. conventional hydraulics.

Adaptive Structures

Active Aeroelastic Wing (AAW)[26] is a technology about to go into the flight demonstration phase on a modified F/A-18. This technology is most applicable to designs requiring additional structural weight to prevent control surface aeroelastic degradation at high dynamic pressure. Instead of stiffening the structure, innovative control logic optimizes the surface usage for given flight conditions to both alleviate maneuver loads and provide control authority. It is not felt that the technology would be well aligned with a B-2 class vehicle, because wing stiffness design is dominated by strength considerations from a variety of sources not including static aeroelasticity as illustrated in figure 24.

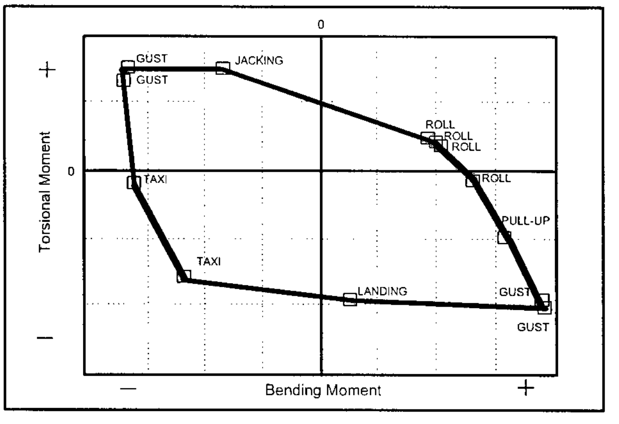

Figure 24 - This load diamond of a B-2 wing station illustrates the wide variety of loading conditions that define the wing stiffness (Roll refers to roll maneuver).

The AAW concept also leans towards larger numbers of control surfaces to provide more design variables to optimize

for various maneuver and dynamic pressure conditions. B-2 class vehicles strive for continuous structure and low control surface activity to minimize radar cross section and improve survivability. AAW was initially conceived for fighter aircraft weight reduction and performance enhancement. This technology may also be conducive to supersonic transports or bombers, where slenderness constraints impose intrinsic stiffness limits, however flutter suppression may be required.

The Twist Adaptive Wing System (TAWS)[27] and Continuous Aerodynamic Control Surface concepts strive for aerodynamic controls which are seamless for both improved aerodynamic performance and survivability. TAWS is geared towards medium to high aspect ratio wings. It incorporates an internal mechanism to twist the wing to provide incremental lift for maneuvering, load alleviation and performance optimization. The TAWS concept has also showed significant potential in reduced manufacturing costs by reduced part count and sealing the structure from environmental damage. Continuous aerodynamic control surfaces technologies can be generally describes as advanced seals which maintain structural continuity for relatively conventional aerodynamic control mechanisms.

Concepts in this class will be of continued interest for military bombers and transports due to multiple benefits provided, particularly survivability. In fact, deformable surfaces were considered in the early B-2 design stages, but were abandoned due to lack of technical readiness and inadequate control authority at low speed.

<u>Summary</u>

Future bomber and large transport designs can clearly benefit from emerging technologies in the following fields:

- Multidisciplinary Frameworks Which Manage and Couple Multidisciplanry Databases and Models in an Automated, Consistent and Robust Fashion
- Practical Methodologies for Incorporating Unsteady Wind Tunnel Pressures into Flutter and Aeroservoelastic Simulations
- Reduced Order Aerodynamic Methods for Aeroservoelastic Simulation
- Embedded Distributed Sensor Networks for Robust Real Time State Determination
- Improved Linearity and Frequency Response Actuation (eliminate deadband)
- Deformable/Adaptive Structures for Improved Aerodynamic Performance and More Affordable and Maintainable Survivability

11. Concluding Remarks

The B-2's unconventional configuration, low wing loading, broad operating envelope, and unique aeroelastic characteristics presented a number of design challenges. The design solution integrates three-axis stability augmentation and vertical gust load alleviation functions into a quad redundant digital flight control system which provide the vehicle outstanding handling and ride qualities throughout the flight envelope.

This paper outlines the multidisciplinary approach to developing the analytical models used in refining and validating the total system design. Some of the unique aeroelastic characteristics have also been discussed. Finally, a technology assessment is performed which discusses design methods and technology improvements in the areas of actuators, sensors, and adaptive structures that could benefit future bombers and large transport aircraft.

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